Concurrency Control

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Outline

What makes a schedule serializable?

Conflict serializability

Precedence graphs

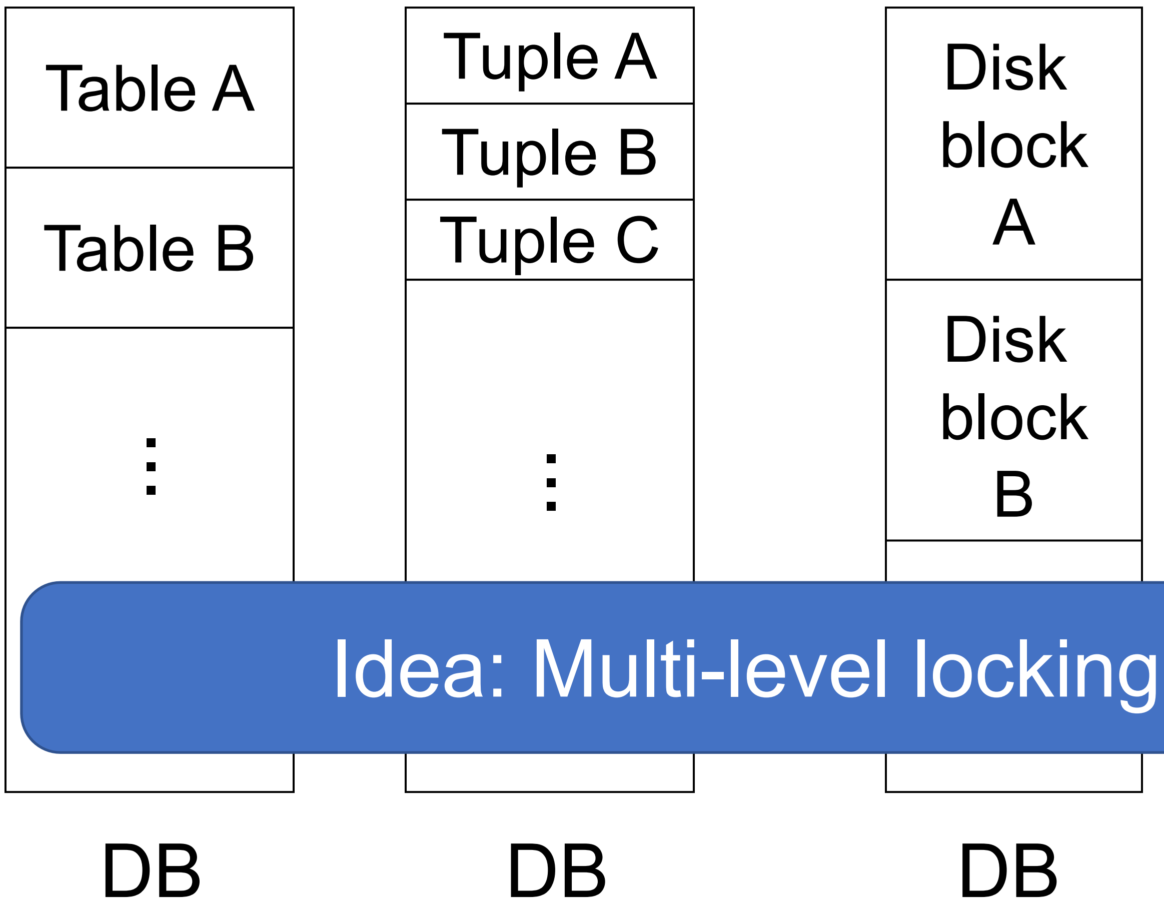
Enforcing serializability via 2-phase locking
- » Shared and exclusive locks
- » Lock tables and multi-level locking

Optimistic concurrency with validation

Concurrency control + recovery

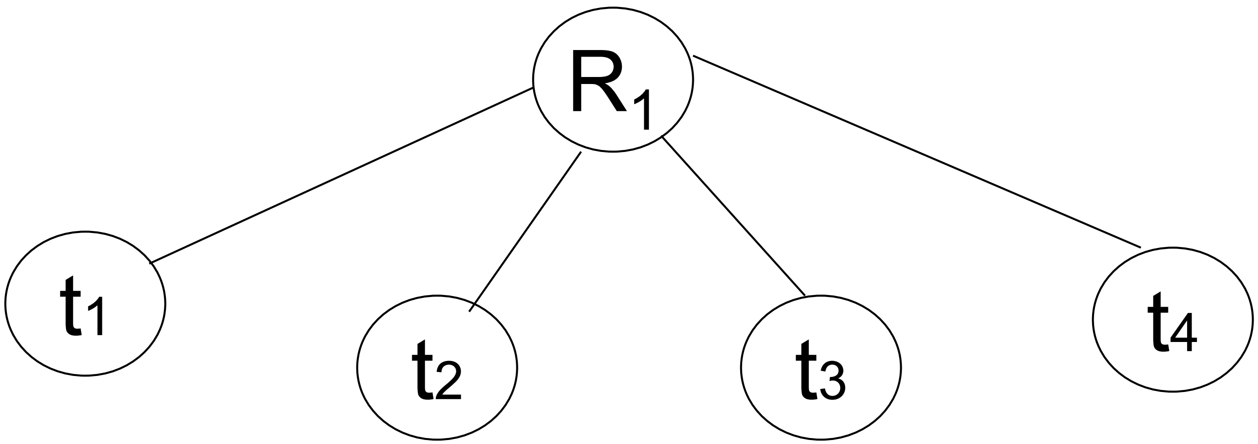
Beyond serializability

Which Objects Do We Lock?

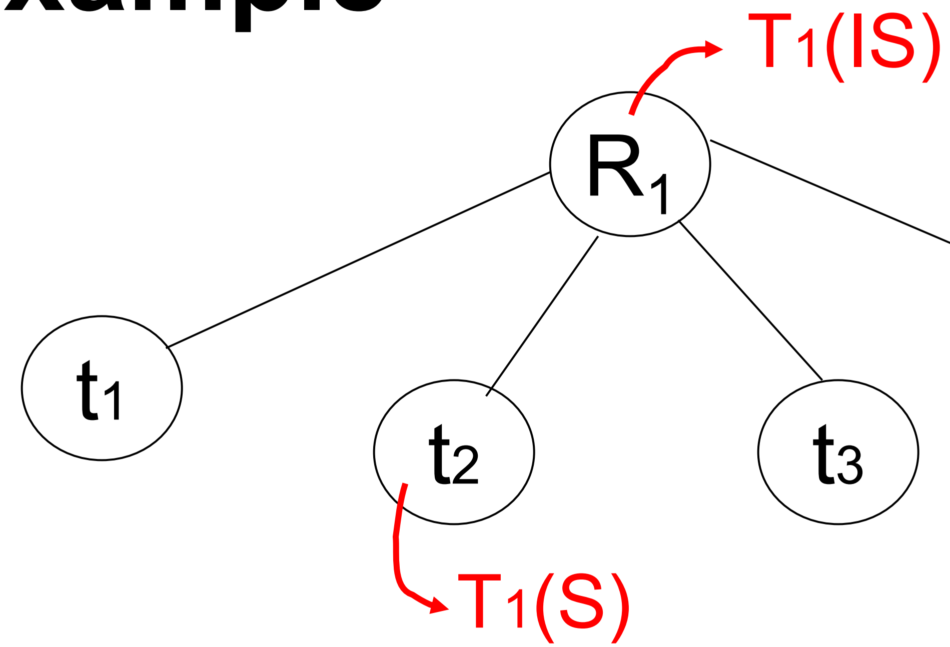


Idea: Multi-level locking

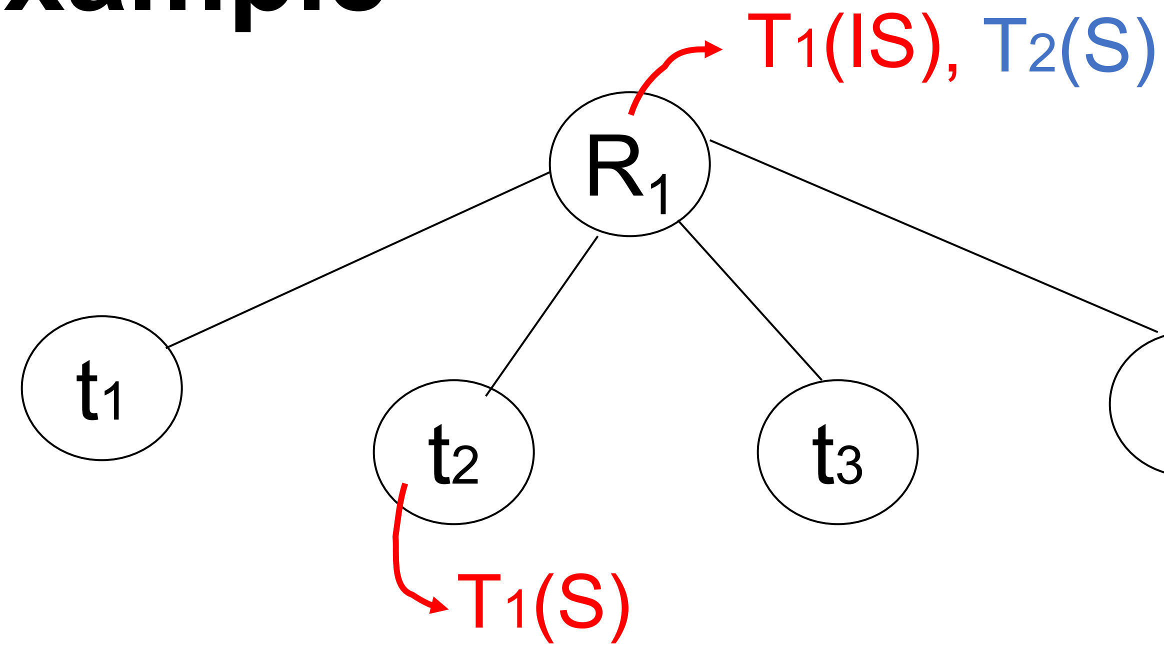
Example



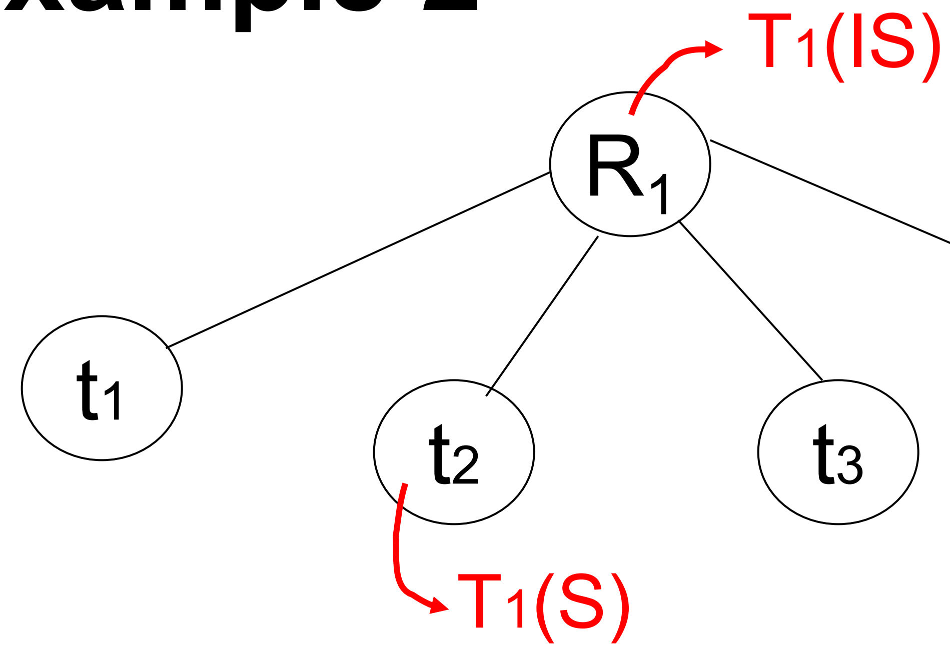
Example



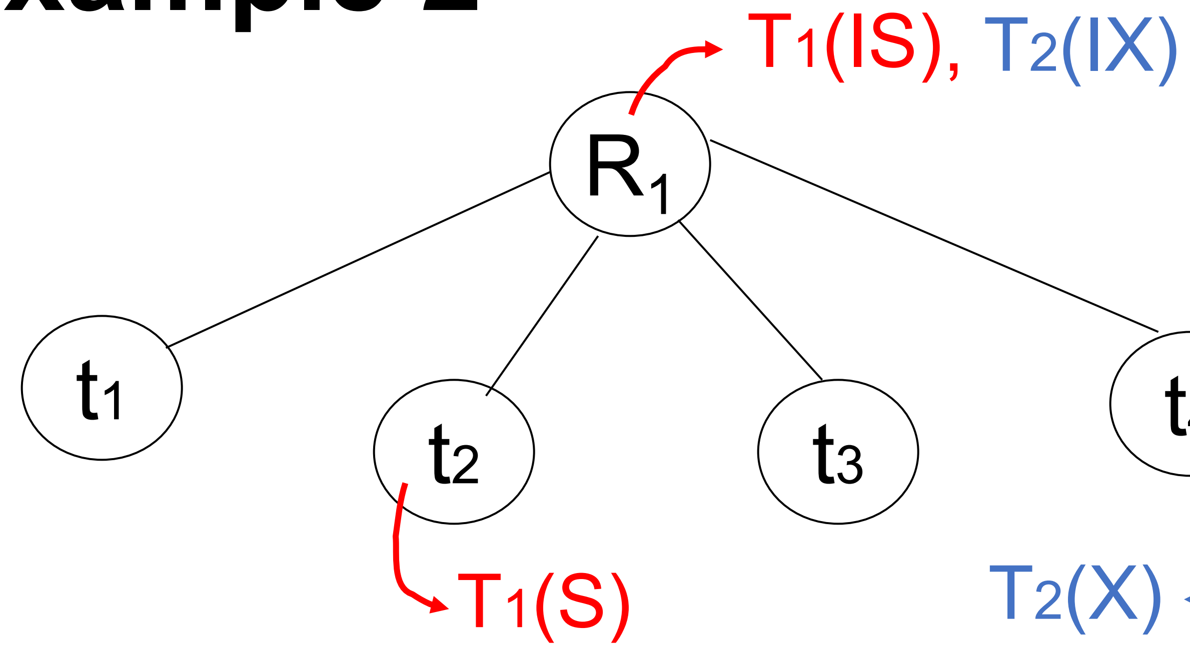
Example



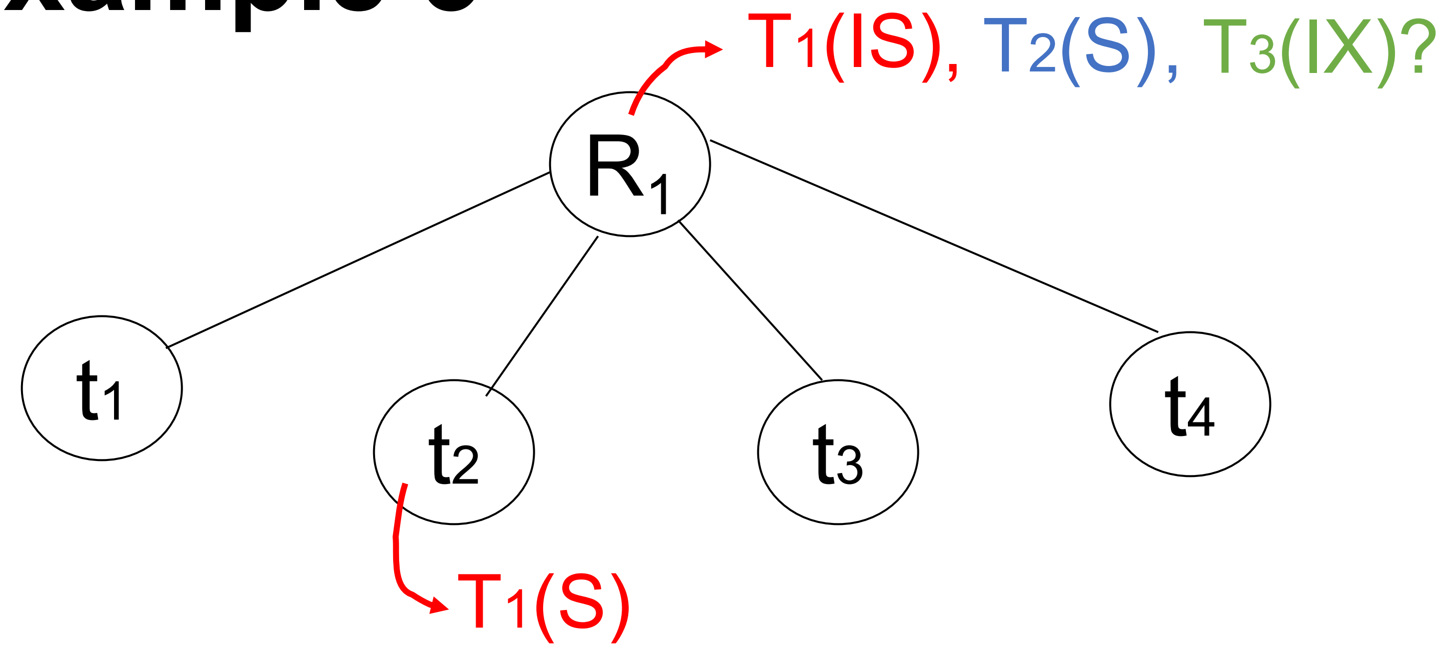
Example 2



Example 2



Example 3

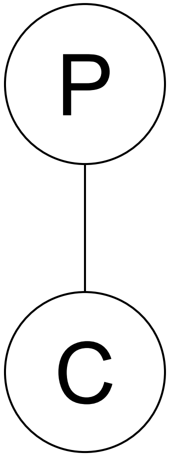


Multiple Granularity Locks

compat		Requestor				
		IS	IX	S	SIX	X
Holder	IS	T	T	T	T	F
	IX	T	T	F	F	F
	S	T	F	T	F	F
	SIX	T	F	F	F	F
	X	F	F	F	F	F

Rules Within A Transaction

Parent locked in	Child can be locked by same transaction in
IS	IS, S
IX	IS, S, IX, X, SIX
S	none
SIX	X, IX, SIX
X	none

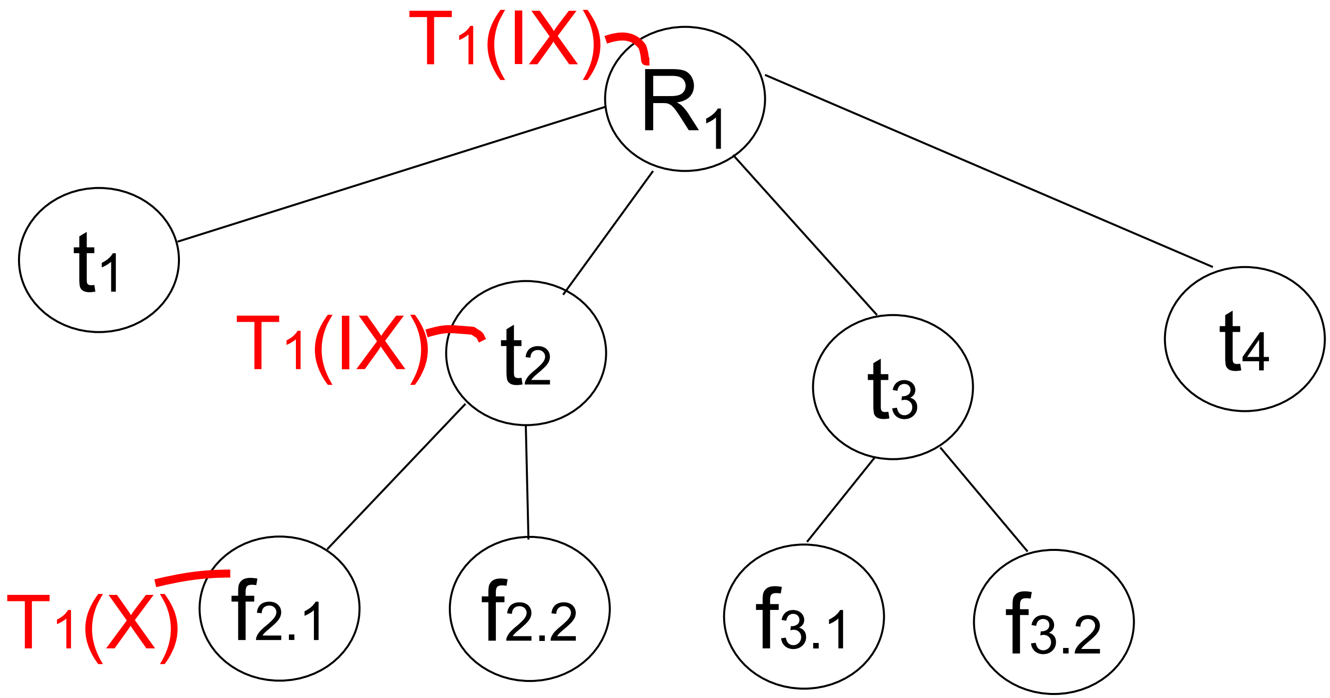


Multi-Granularity 2PL Rules

1. Follow multi-granularity compat function
2. Lock root of tree first, any mode
3. Node Q can be locked by T_i in S or IS only if parent(Q) locked by T_i in IX or IS
4. Node Q can be locked by T_i in X, SIX, IX only if parent(Q) locked by T_i in IX, SIX
5. T_i is two-phase
6. T_i can unlock node Q only if none of Q's children are locked by T_i

Exercise:

Can T_2 access object $f_{2.2}$ in X mode? What locks will T_2 get?



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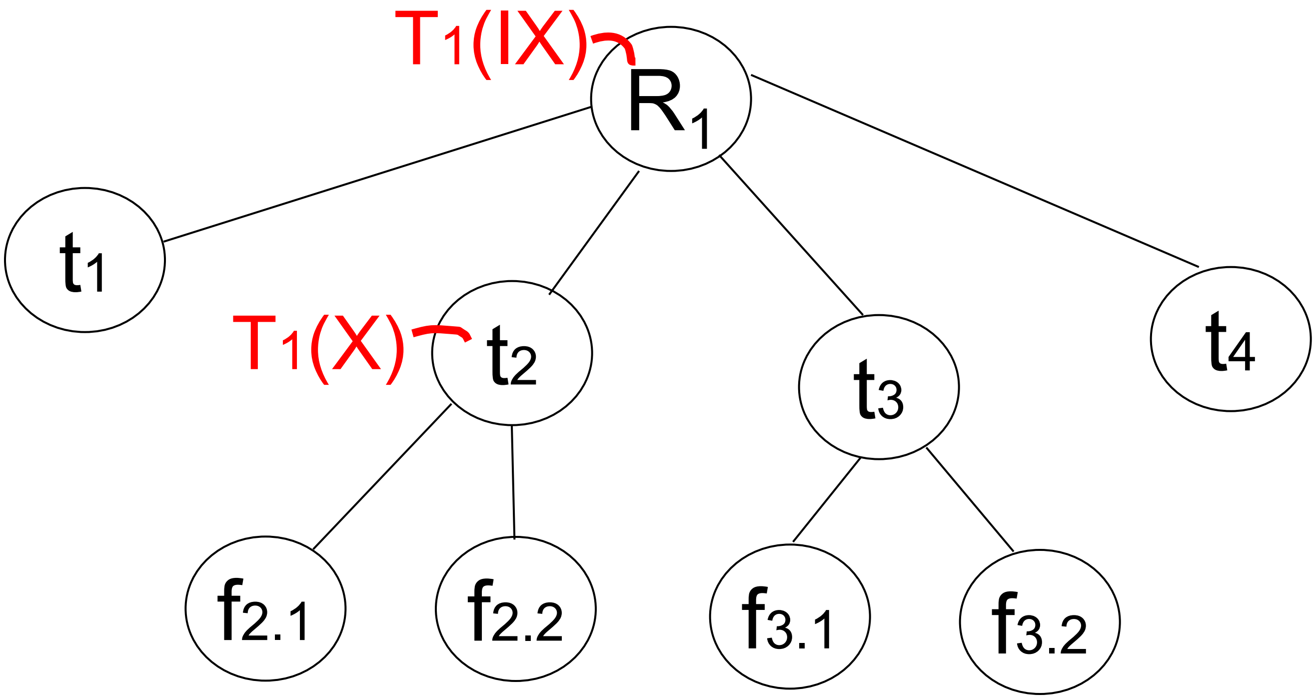
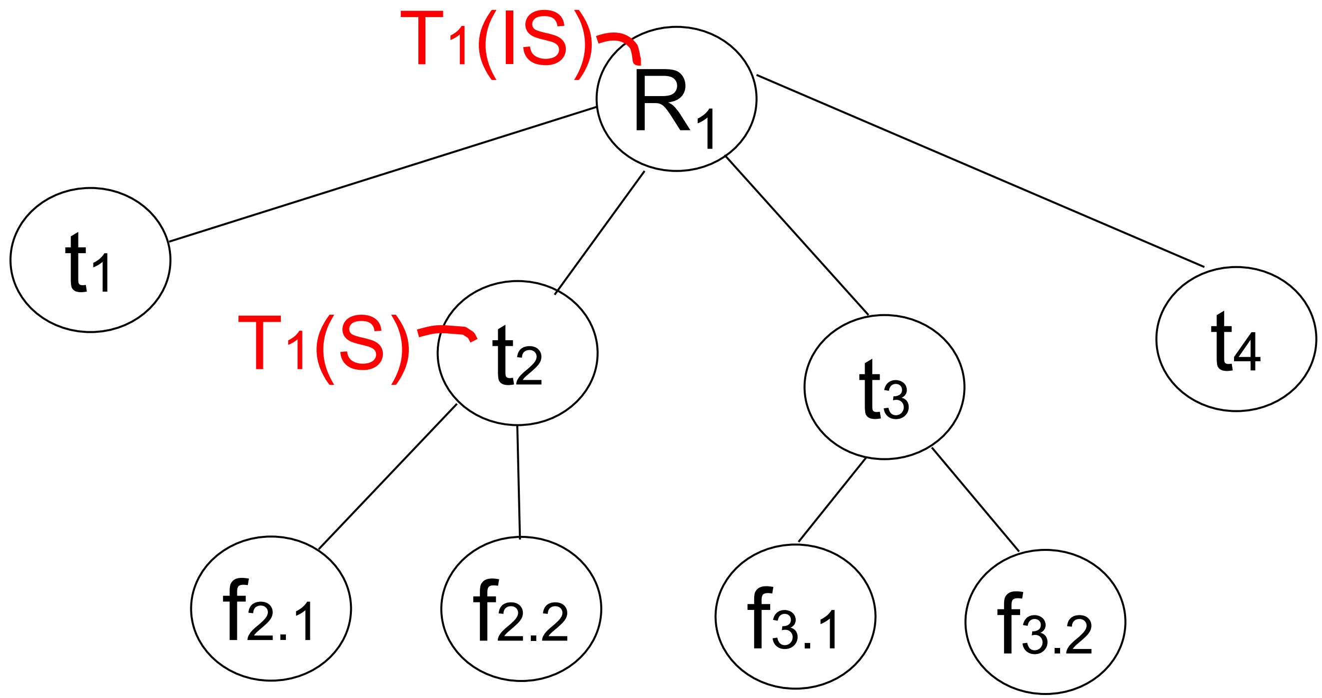
Can T_2 access object $f_{2.2}$ in X mode? What locks will T_2 get?



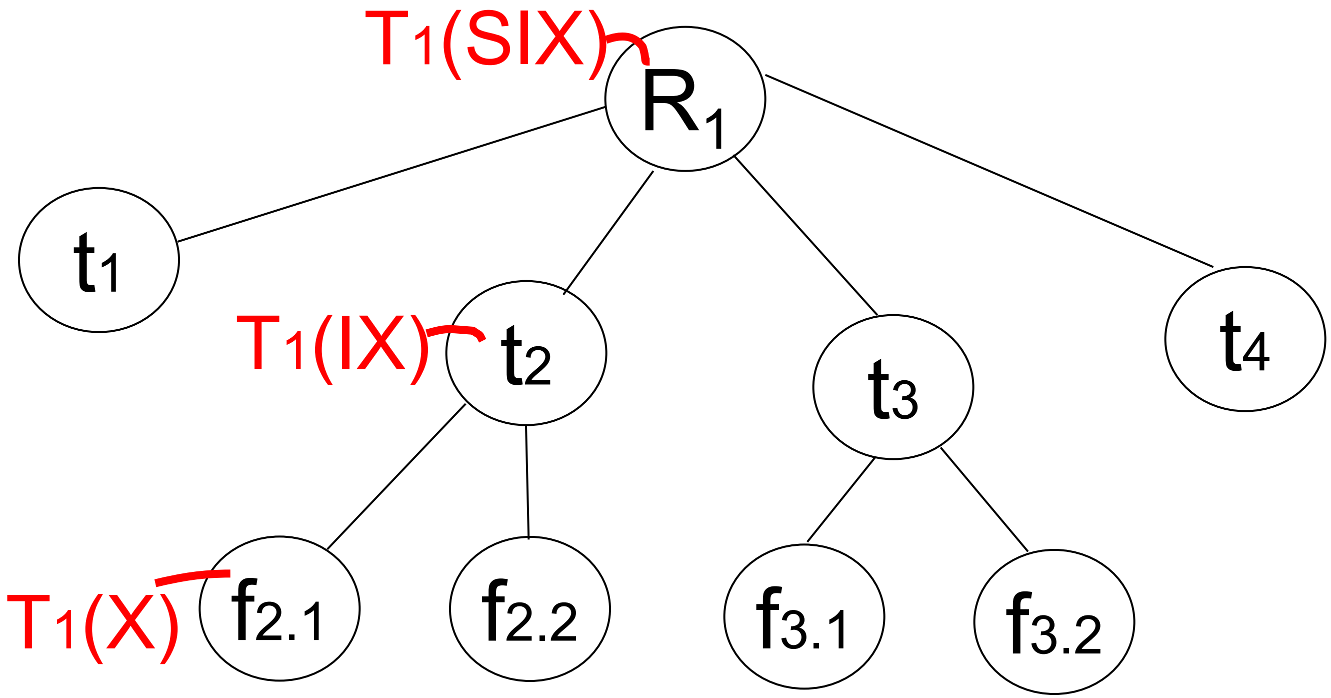
Exercise:

Can T_2 access object $f_{3.1}$ in X mode? What locks will T_2 get?



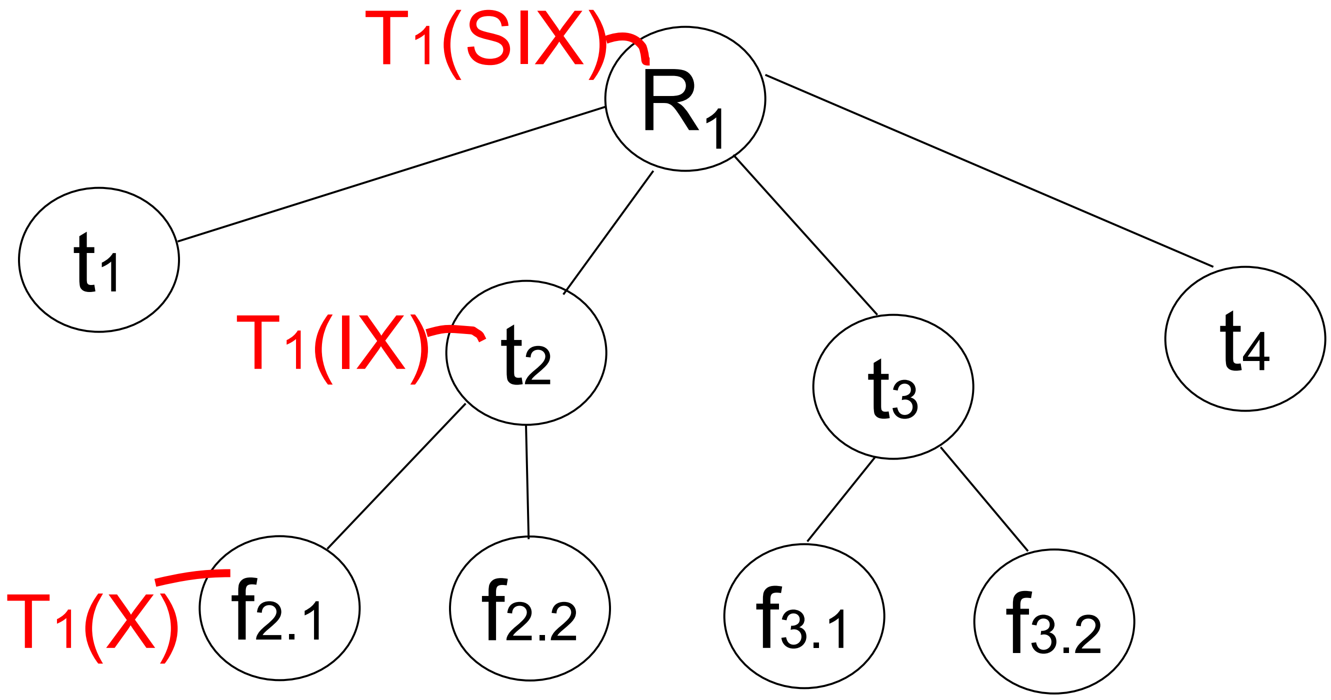
Exercise:

Can T_2 access object $f_{2.2}$ in S mode? What locks will T_2 get?

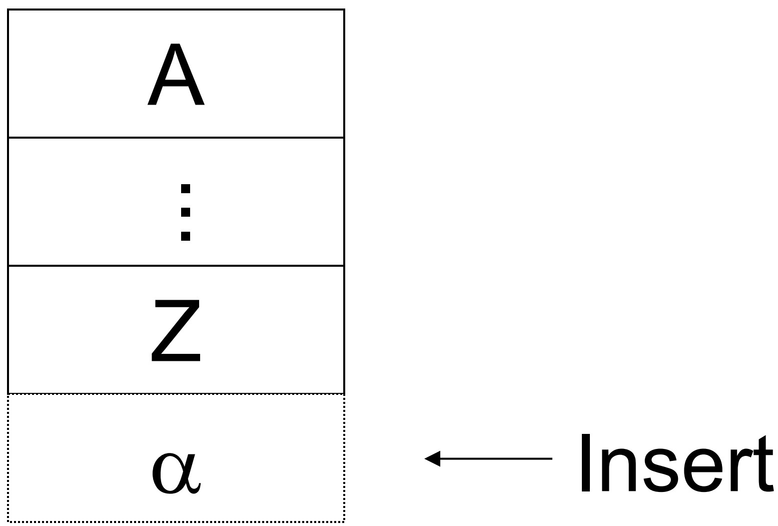


Exercise:

Can T_2 access object $f_{2.2}$ in X mode? What locks will T_2 get?



Insert + Delete Operations



Changes to Locking Rules:

1. Get exclusive lock on A before deleting A

2. When T_i inserts an object A, T_i receives an exclusive lock on A

Still Have Problem: Phantoms

Example: relation R (id, name,…)

constraint: id is unique key

use tuple locking

R

	id	name	….
o_1	55	Smith	
o_2	75	Jones	

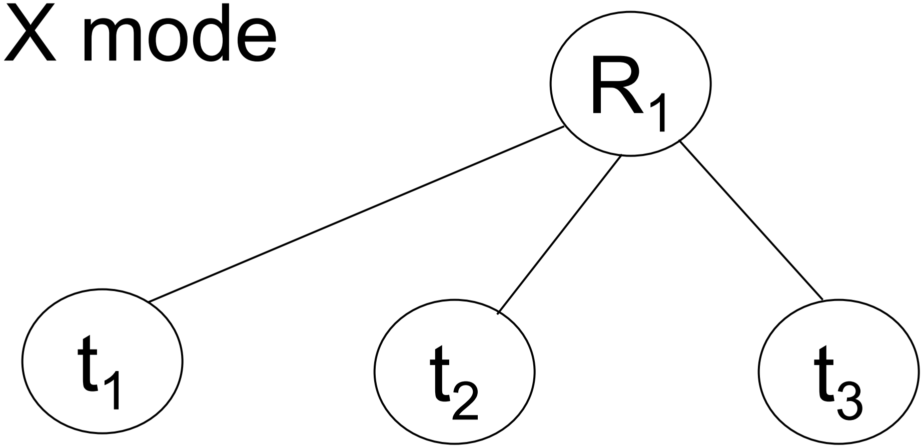
T_1: Insert <12,Mary,…> into R
T_2: Insert <12,Sam,…> into R

T1	T2
l-$S_1(o_1)$	l-$S_2(o_1)$
l-$S_1(o_2)$	l-$S_2(o_2)$
Check Constraint	Check Constraint
⋮	⋮
Insert o_3[12,Mary,..]	
	Insert o_4[12,Sam,..]

Solution

Use multiple granularity tree

Before insert of node N,
lock parent(N) in X mode

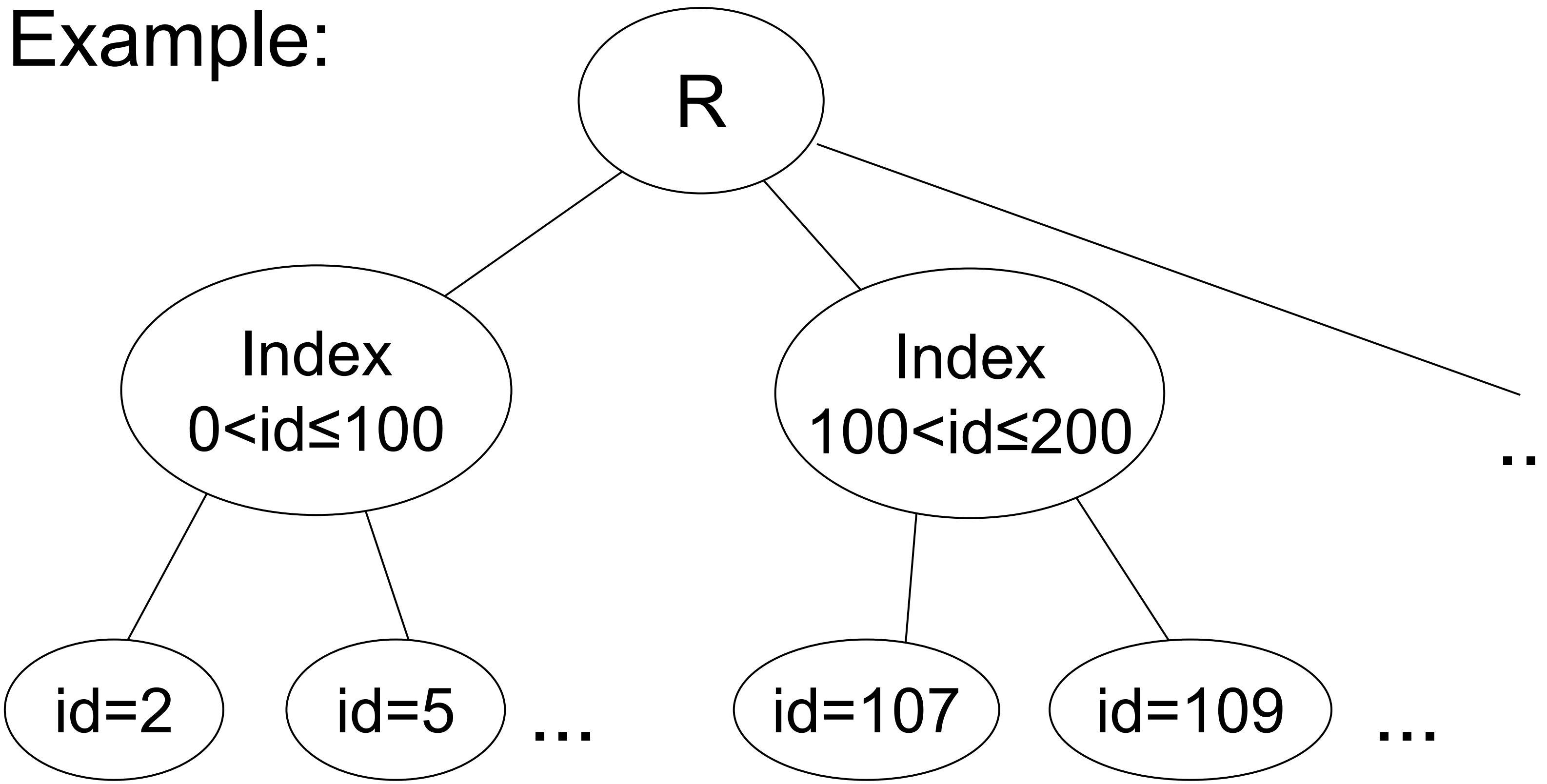


Back to Example

T_1: Insert<12,Mary>	T_2: Insert<12,Sam>
T_1	T_2
$l\text{-}X_1(R)$	
	$l\text{-}X_2(R)$ ← delayed
Check constraint	
Insert<12,Mary>	
$U_1(R)$	
	$l\text{-}X_2(R)$
	Check constraint
	Oops! id=12 already in R!

Instead of Locking R, Can Use Index Nodes for Ranges

Example:



How Is Locking Implemented In Practice?

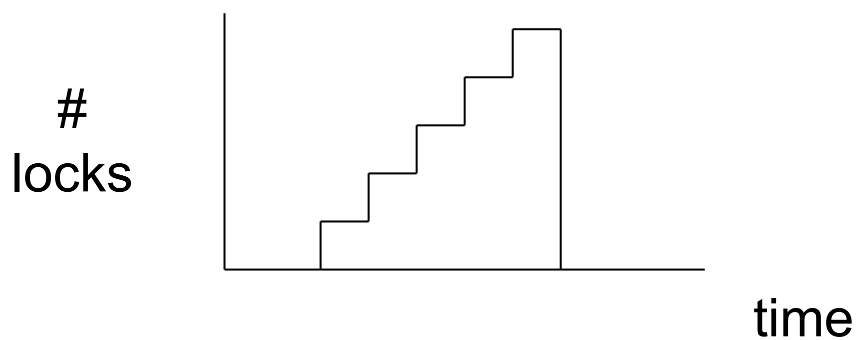
Every system is different (e.g., may not even provide conflict serializable schedules)

But here is one (simplified) way ...

Sample Locking System

1. Don't ask transactions to request/release locks: just get the weakest lock for each action they perform

2. Hold all locks until the transaction commits



Sample Locking System

Under the hood: lock manager that keeps track of which objects are locked

» E.g. hash table

Also need good ways to block transactions until locks are available, and to find deadlocks

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Beyond serializability

Validation Approach

Transactions have 3 phases:

1. Read
   » Read all DB values needed
   » Write to temporary storage
   » No locking

2. Validate
   » Check whether schedule so far is serializable

3. Write
   » If validate OK, write to DB

Key Idea

Make validation atomic

If the validation order is T_1, T_2, T_3, …, then resulting schedule will be conflict equivalent to $S_s = T_1, T_2, T_3, \ldots$

Implementing Validation

System keeps track of two sets:

FIN = transactions that have finished phase 3 (write phase) and are all done

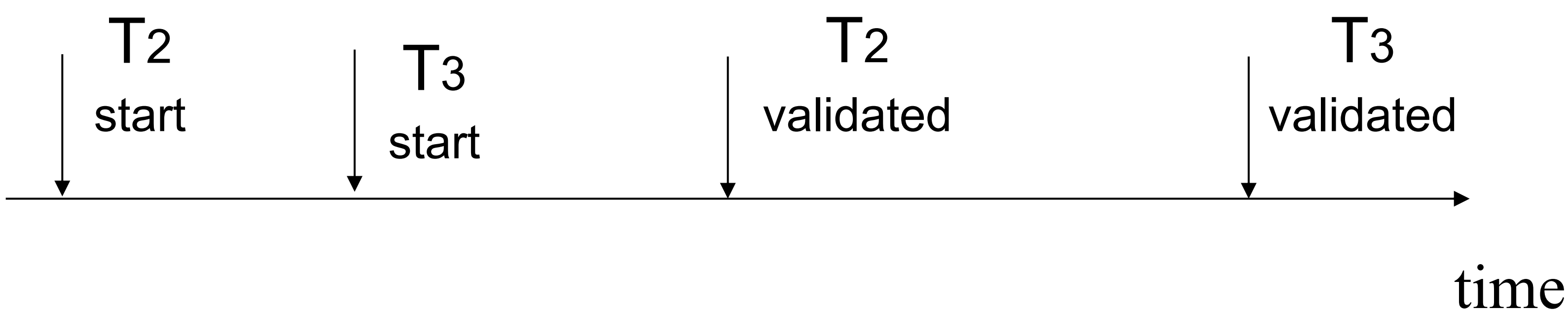
VAL = transactions that have successfully finished phase 2 (validation)

Example That Validation Must Prevent:

$RS(T_2)=\{B\}$ $\qquad$ $RS(T_3)=\{A,B\}$ $\neq \emptyset$

$\cap$

$WS(T_2)=\{B,D\}$ $\qquad$ $WS(T_3)=\{C\}$



Example That Validation Must Allow:

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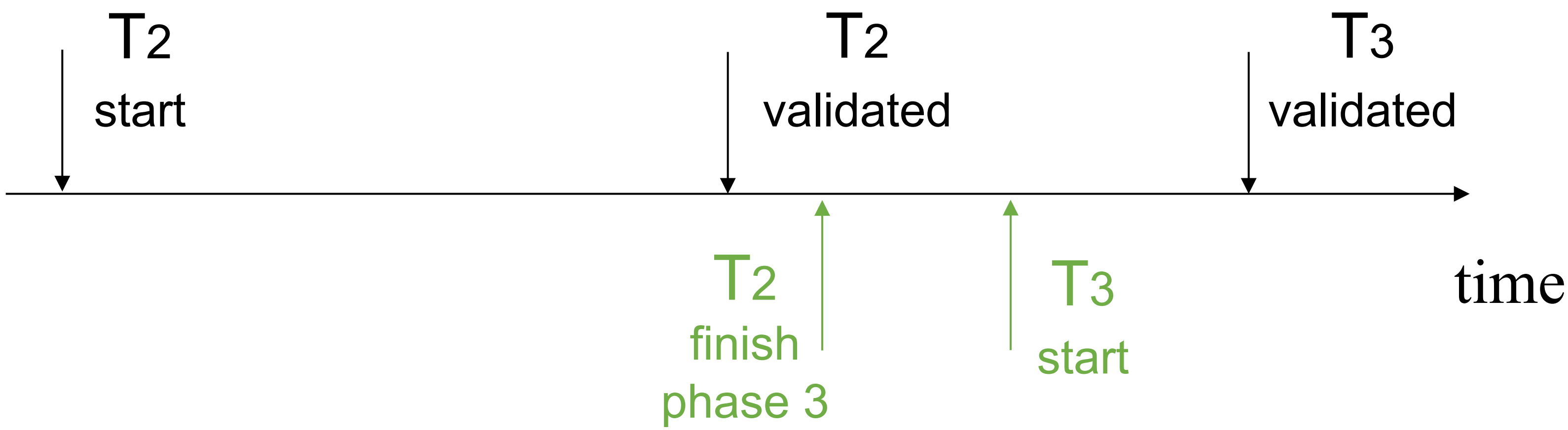
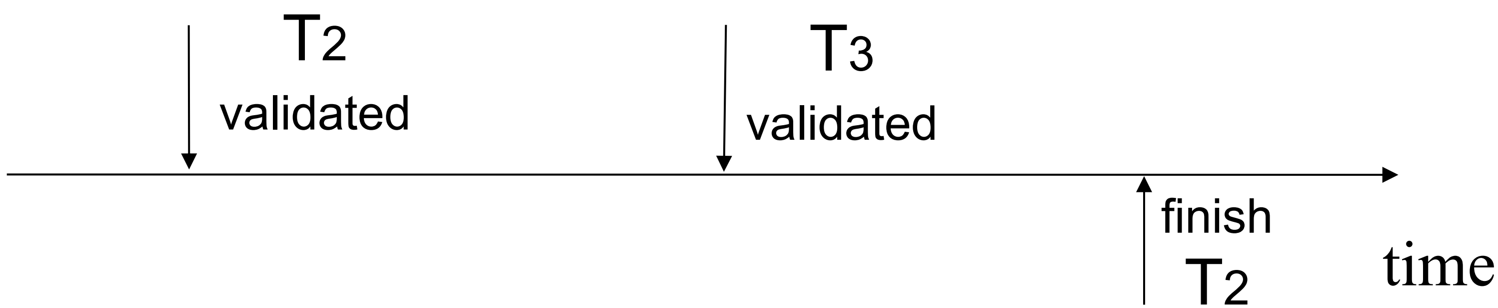


Another Thing Validation Must Prevent:

$RS(T_2)=\{A\}$ $RS(T_3)=\{A,B\}$

$WS(T_2)=\{D,E\}$ $WS(T_3)=\{C,D\}$



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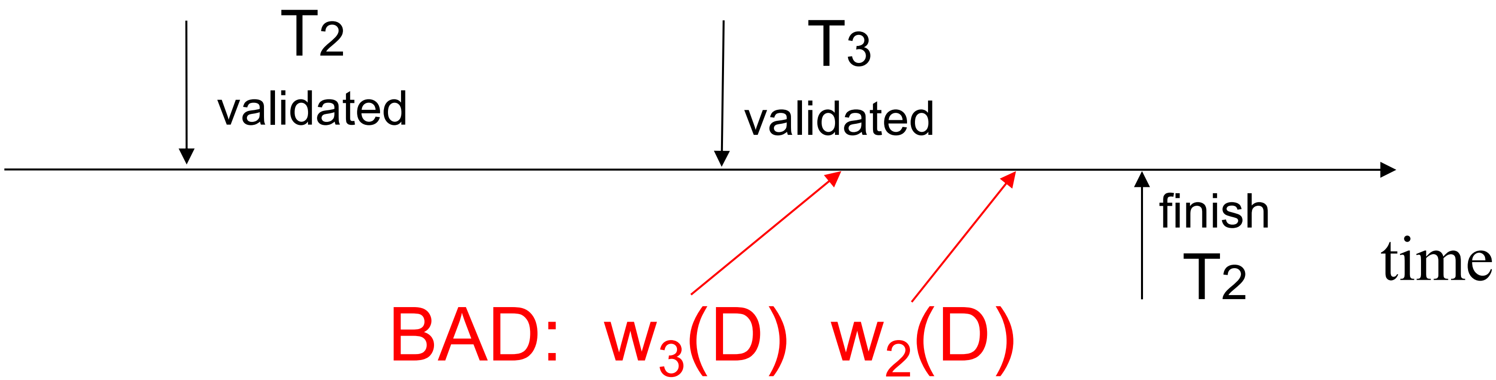

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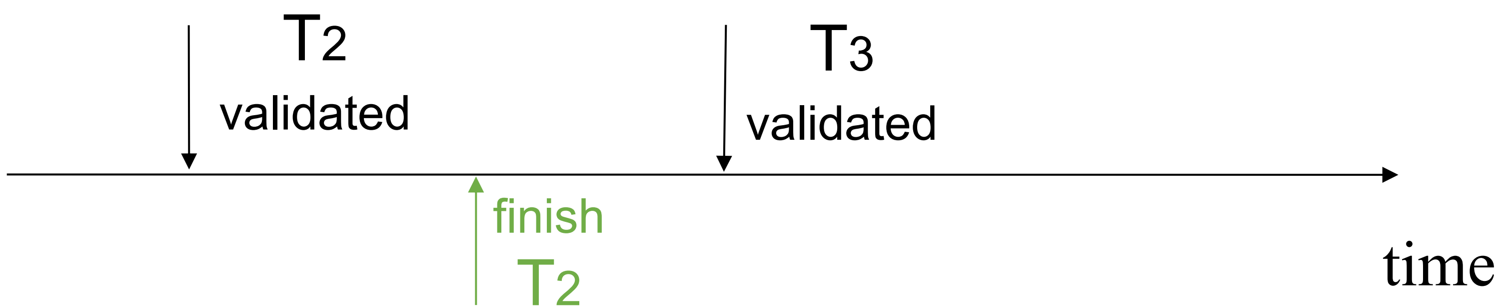


Validation Rules for T_j:

when T_j starts phase 1:

$\text{ignore}(T_j) \leftarrow \text{FIN}$

at T_j Validation:

if $\text{Check}(T_j)$ then

$\text{VAL} \leftarrow \text{VAL} \cup \{T_j\}$

do write phase

$\text{FIN} \leftarrow \text{FIN} \cup \{T_j\}$

Check(T_j)

for $T_i \in$ VAL – ignore(T_j) do

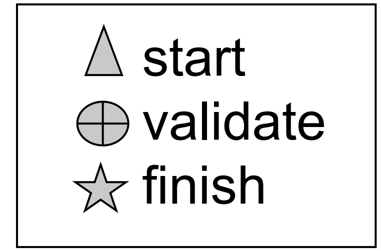
  if (WS(T_i) ∩ RS(T_j) ≠ ∅ or

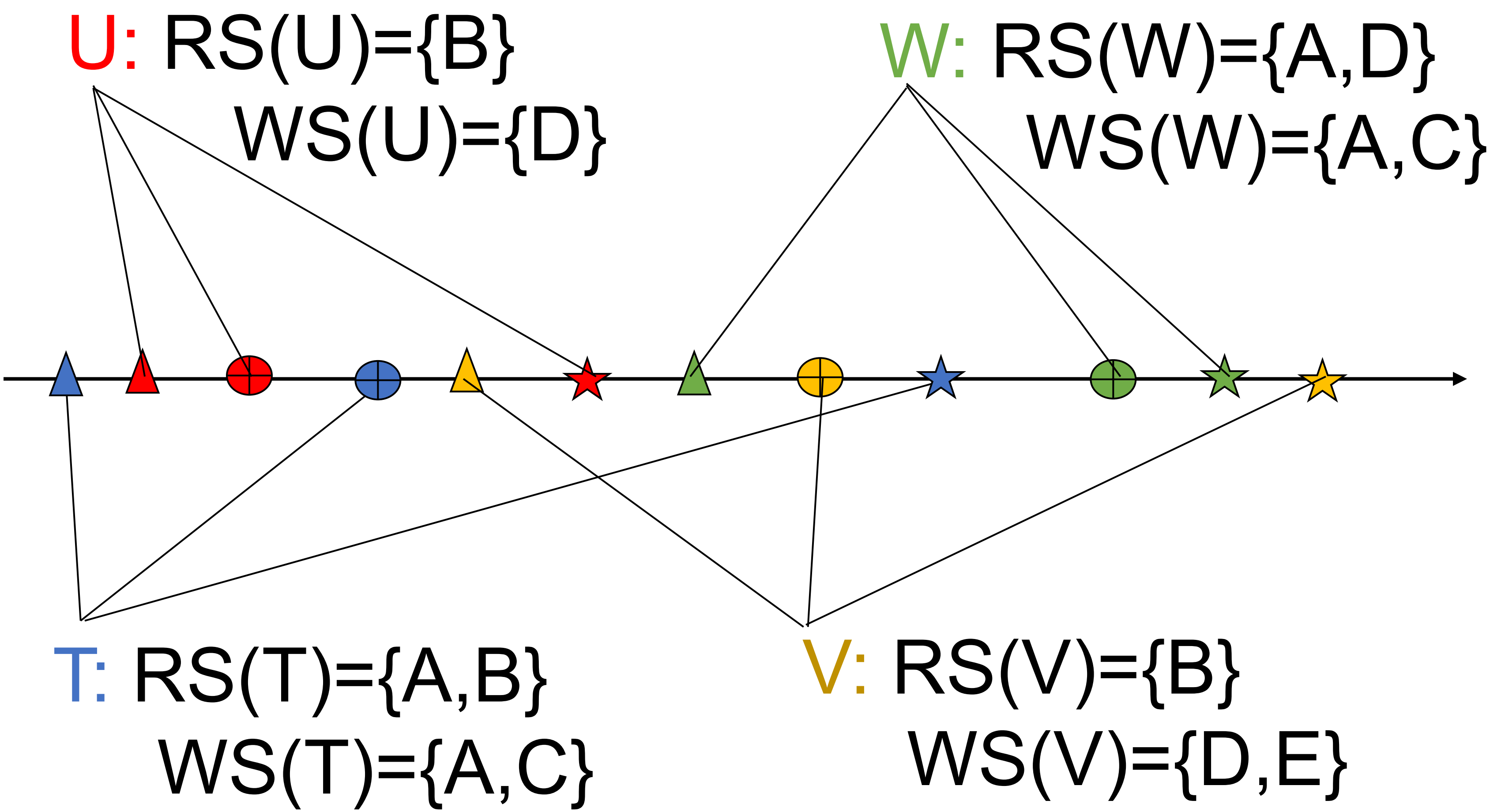
    ($T_i \notin$ FIN and WS(T_i) ∩ WS(T_j) ≠ ∅))

      then return false

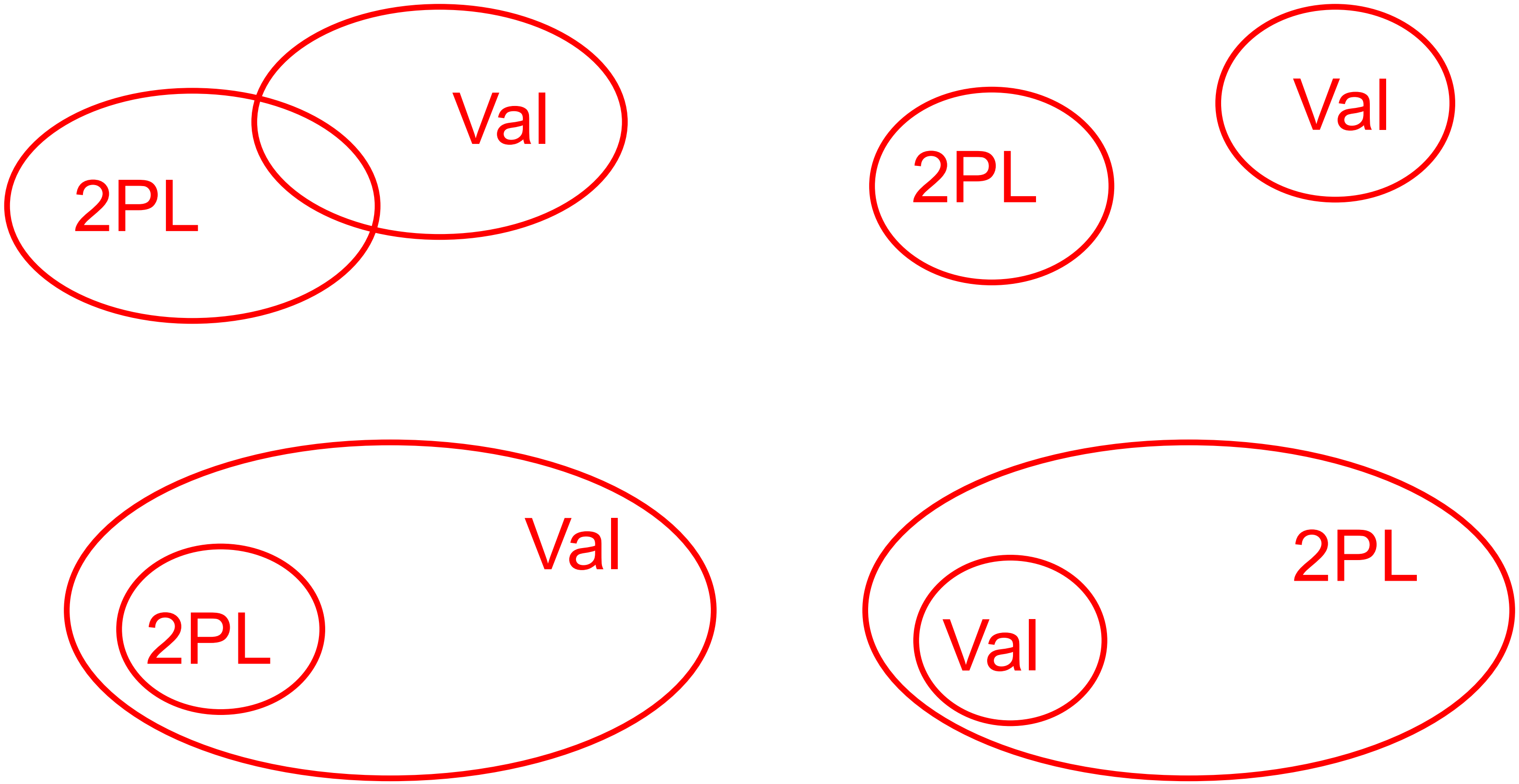
return true

Exercise


start
validate
finish


U: RS(U)={B}
WS(U)={D}
W: RS(W)={A,D}
WS(W)={A,C}
T: RS(T)={A,B}
WS(T)={A,C}
V: RS(V)={B}
WS(V)={D,E}

Is Validation = 2PL?



S: $w_2(y)\ w_1(x)\ w_2(x)$

Achievable with 2PL?

Achievable with validation?

S: $w_2(y)\ w_1(x)\ w_2(x)$

S can be achieved with 2PL:
$l_2(y)\ w_2(y)\ l_1(x)\ w_1(x)\ u_1(x)\ l_2(x)\ w_2(x)\ u_2(x)\ u_2(y)$

S cannot be achieved by validation:
The validation point of T_2, val_2, must occur before $w_2(y)$ since transactions do not write to the database until after validation. Because of the conflict on x, $val_1 < val_2$, so we must have something like:

S: $val_1\ \ val_2\ \ w_2(y)\ \ w_1(x)\ \ w_2(x)$

With the validation protocol, the writes of T_2 should not start until T_1 is all done with writes, which is not the case.

Validation Subset of 2PL?

Possible proof (Check!):

- » Let S be validation schedule
- » For each T in S insert lock/unlocks, get S':
  - At T start: request read locks for all of RS(T)
  - At T validation: request write locks for WS(T); release read locks for read-only objects
  - At T end: release all write locks
- » Clearly transactions well-formed and 2PL
- » Must show S' is legal (next slide)

Validation Subset of 2PL?

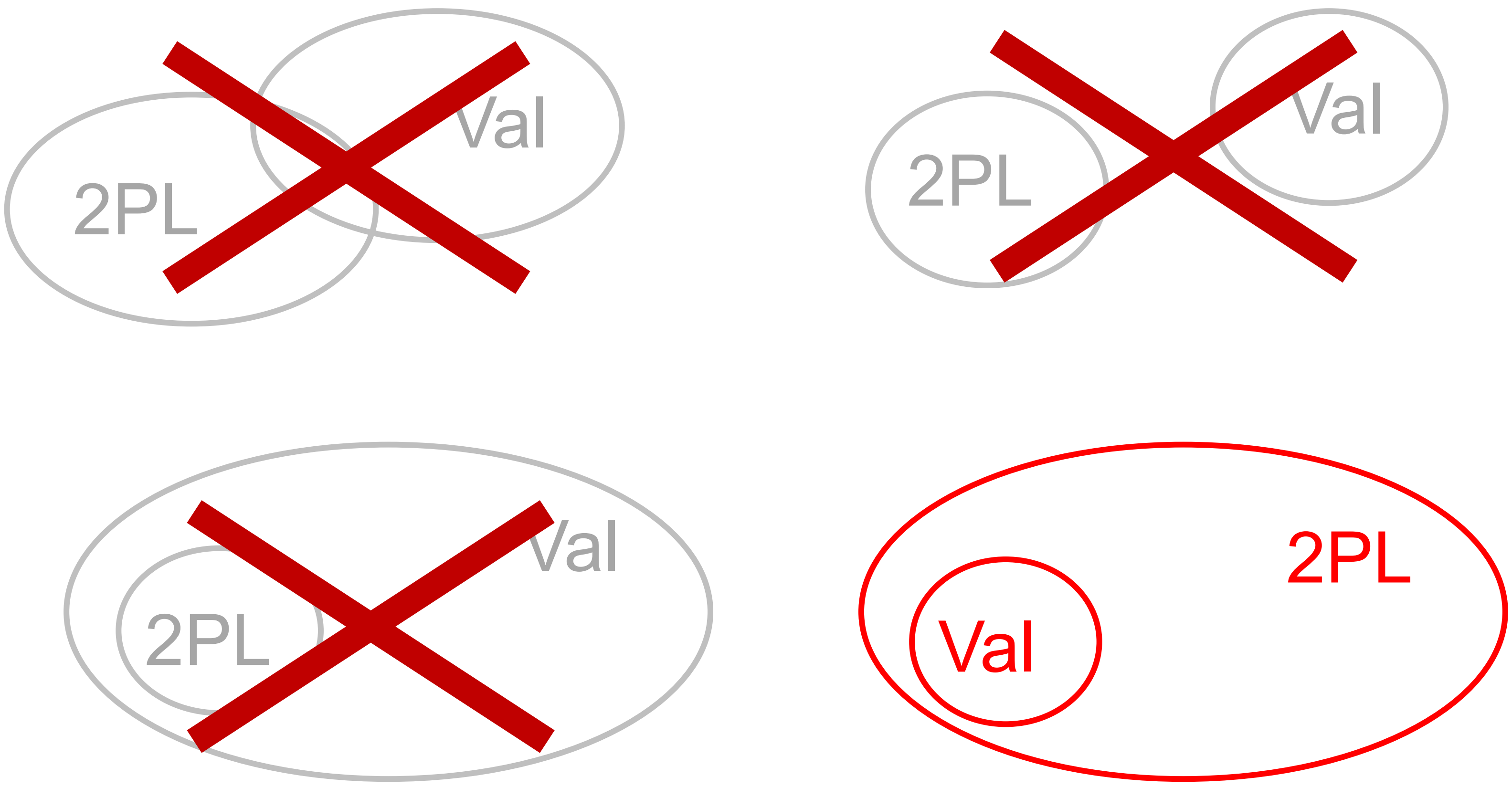
Say S' not legal (due to w-r conflict):
S': ... l1(x)   w2(x) r1(x)   val1 u1(x) ...

- At val1: T2 not in Ignore(T1); T2 in VAL
- T1 does not validate: $WS(T2) \cap RS(T1) \neq \emptyset$
- contradiction!

Say S' not legal (due to w-w conflict):
S': ... val1 l1(x)   w2(x) w1(x)   u1(x) ...

- Say T2 validates first (proof similar if T1 validates first)
- At val1: T2 not in Ignore(T1); T2 in VAL
- T1 does not validate:
  $T2 \notin FIN$ AND $WS(T1) \cap WS(T2) \neq \emptyset$)
- contradiction!

Is Validation = 2PL?



When to Use Validation?

Validation performs better than locking when:

» Conflicts are rare

» System resources are plentiful

» Have tight latency constraints

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Beyond serializability

Concurrency Control & Recovery

Example: **T_j** **T_i**

T_j	T_i
⋮	⋮
$w_j(A)$	⋮
	$r_i(A)$
⋮	Commit T_i
⋮	⋮
Abort T_j	

Non-persistent commit (bad!)

avoided by **recoverable** schedules

Concurrency Control & Recovery

Example: **T_j** **T_i**

T_j	T_i
⋮	⋮
$w_j(A)$	⋮
⋮	$r_i(A)$
⋮	$w_i(B)$
	⋮
Abort T_j	
	[Commit T_i]

Cascading rollback (bad!)

avoided by **avoids-cascading-rollback (ACR)** schedules

Core Problem

Schedule is conflict serializable

$T_j \longrightarrow T_i$

But not recoverable

To Resolve This

Need to mark the “final” decision for each transaction in our schedules:

» **Commit decision:** system guarantees transaction will or has completed

» **Abort decision:** system guarantees transaction will or has been rolled back

Model This as 2 New Actions:

c_i = transaction T_i commits

a_i = transaction T_i aborts

Back to Example

T_j	T_i
⋮	⋮
$w_j(A)$	
	$r_i(A)$
⋮	
	⋮
	c_i $\leftarrow$ can we commit here?

Definition

T_i **reads from** T_j in S ($T_j \Rightarrow_S T_i$) if:

1. $w_j(A) <_S r_i(A)$
2. $a_j \not<_S r(A)$ ($\not<_S$: does not precede)
3. If $w_j(A) <_S w_k(A) <_S r_i(A)$ then $a_k <_S r_i(A)$

Definition

Schedule S is **recoverable** if

whenever $T_j \Rightarrow_S T_i$ and $j \neq i$ and $c_i \in S$

then $c_j <_S c_i$

Notes

In all transactions, reads and writes must precede commits or aborts

⇔ If $c_i \in T_i$, then $r_i(A) < a_i$, $w_i(A) < a_i$

⇔ If $a_i \in T_i$, then $r_i(A) < a_i$, $w_i(A) < a_i$

Also, just one of c_i, a_i per transaction

How to Achieve Recoverable Schedules?

With 2PL, Hold Write Locks Until Commit (“Strict 2PL”)

T_j	T_i
$W_j(A)$	⋮
⋮	⋮
C_j	⋮
$u_j(A)$	⋮
⋮	$r_i(A)$

With Validation, No Change!

Each transaction’s validation point is its commit point, and only write after

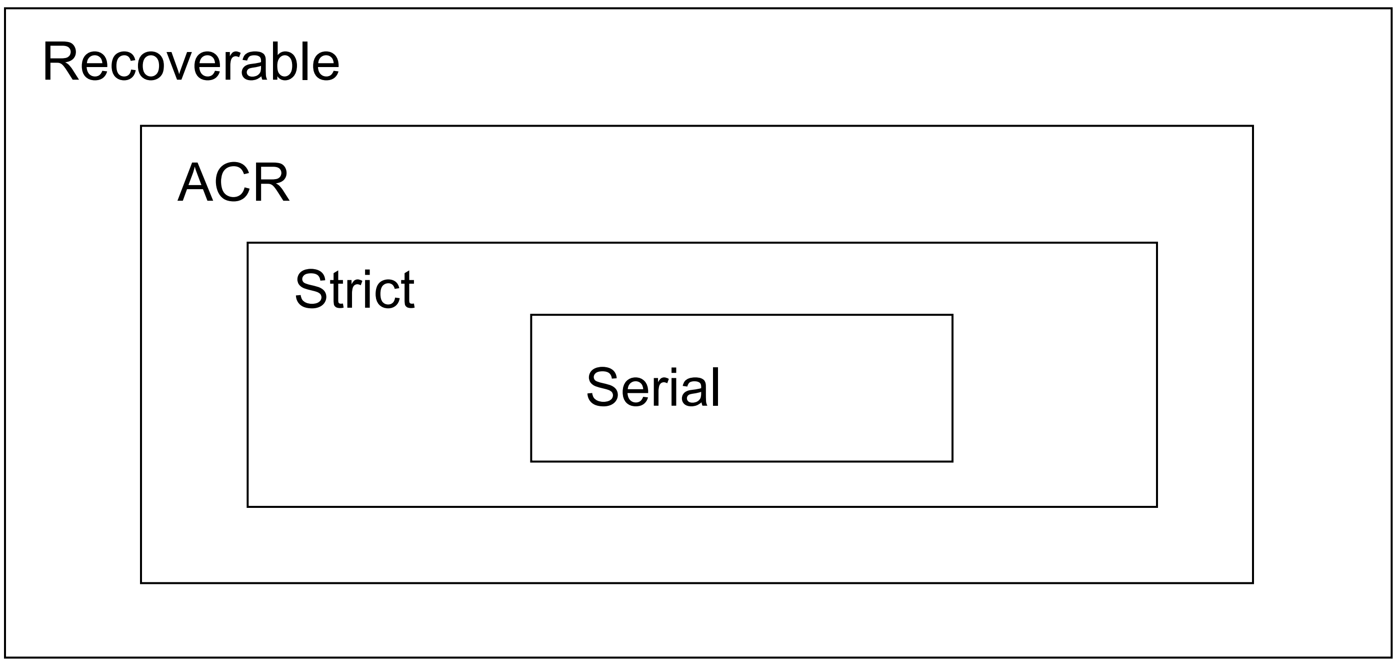
Definitions

S is **recoverable** if each transaction commits only after all transactions from which it read have committed

S **avoids cascading rollback** if each transaction may read only those values written by committed transactions

S is **strict** if each transaction may read and write only items previously written by committed transactions (≡ strict 2PL)

Relationship of Recoverable, ACR & Strict Schedules



Examples

Recoverable:

$w_1(A)\ w_1(B)\ w_2(A)\ r_2(B)\ c_1\ c_2$

Avoids Cascading Rollback:

$w_1(A)\ w_1(B)\ w_2(A)\ c_1\ r_2(B)\ c_2$

Strict:

$w_1(A)\ w_1(B)\ c_1\ w_2(A)\ r_2(B)\ c_2$

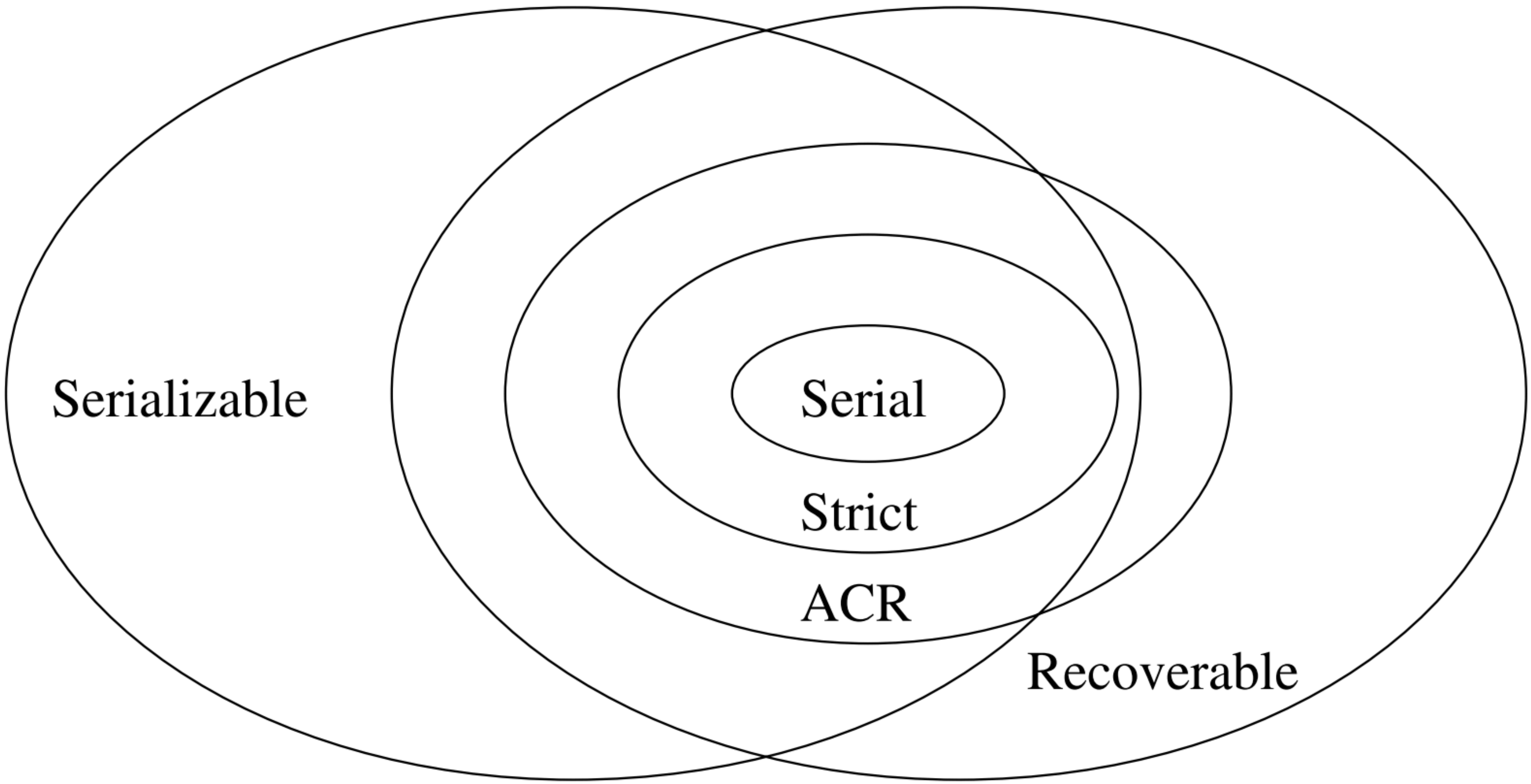
Recoverability & Serializability

Every strict schedule is serializable

Proof: equivalent to serial schedule based on the order of commit points

» Only read/write from previously committed transactions

Recoverability & Serializability



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Weaker Isolation Levels

Dirty reads: Let transactions read values written by other uncommitted transactions

» Equivalent to having long-duration write locks, but no read locks

Read committed: Can only read values from committed transactions, but they may change

» Equivalent to having long-duration write locks (X) and short-duration read locks (S)

Weaker Isolation Levels

Repeatable reads: Can only read values from committed transactions, and each value will be the same if read again

» Equivalent to having long-duration read & write locks (X/S) but not table locks for insert

Remaining problem: phantoms!

Weaker Isolation Levels

Snapshot isolation: Each transaction sees a consistent snapshot of the whole DB (as if we saved all committed values when it began)

» Often implemented with multi-version concurrency control (MVCC)

Still has some anomalies! Example?

Weaker Isolation Levels

Snapshot isolation: Each transaction sees a consistent snapshot of the whole DB (as if we saved all committed values when it began)

» Often implemented with multi-version concurrency control (MVCC)

Write skew anomaly: txns write different values

» Constraint: $A+B \geq 0$

» T_1: read A, B; if $A+B \geq 1$, subtract 1 from A

» T_2: read A, B; if $A+B \geq 1$, subtract 1 from B

» Problem: what if we started with A=1, B=0?

Interesting Fact

Oracle calls their snapshot isolation level "serializable", and doesn't provide serializable

Many other systems provide snapshot isolation as an option

» MySQL, PostgreSQL, MongoDB, SQL Server